Parameter optimization for selective harvesting in cauliflower (*Brassica oleracea*) using response surface methodology

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ABSTRACT

Manual harvesting of cauliflower (*Brassica oleracea* var. *botrytis*) is time-consuming, costly, and labour-intensive, necessitating the development of mechanized solutions. This research focuses on optimizing the operating parameters, namely the shaft angular speed and forward speed, for developing the intelligent selective harvesting prototype of cauliflower to enhance harvest success, reduce damage, and minimize cycle time. A laboratory setup was established at ICAR-Indian Agricultural Research Institute, New Delhi during 2022-23, which consisted of a prototype harvesting unit, prototype pulling unit, and plant holding unit. The physical properties of two cauliflower varieties, Pusa Meghna, and Pusa Sharad, were measured. An experimental plan was designed to optimize the operating parameters using response surface methodology (RSM) to enhance performance. The optimized forward speed and shaft angular speed were found to be 0.62 km/h, and 0.36 rad/s, respectively. Regression models were developed to predict all responses for varieties and all prediction errors were found to be less than $\pm 10\%$, indicating the reliability of the developed models. The study aimed to help in the development of an intelligent cauliflower harvester suitable for small-scale growers in India.

Keywords: Chain-saw cutting mechanism, Operating parameters, Response surface methodology, Selective cauliflower harvesting

Cauliflower (*Brassica oleracea* var. *botrytis*) is a major cole crop, belonging to the Brassicaceae family. India is the second-largest producer of cauliflower globally, accounting for 34.6% of global production (FAO 2020). The country has a cauliflower cultivation area of 485,000 ha, producing 9,536,000 metric tonnes. In India, major cauliflower growing states are West Bengal, Madhya Pradesh, Bihar, Gujarat, Odisha, and Haryana (MoA and FW 2022). Manual harvesting of cauliflower is time-consuming, expensive, and heavily reliant on labour using knife/sickles. This method can account for up to 50% of the production costs for cole crops (Anonymous 2018). In addition, harvesting cauliflower is challenging due to uneven ripening, requiring multiple rounds of harvesting. However, various mechanization

¹ICAR-Indian Agricultural Research Institute, New Delhi; ²Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra; ³ICAR-Indian Agricultural Statistics Research Institute, New Delhi; ⁴ICAR-Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh; ⁵ICAR- Research Complex for NEH Region, Umiam, Meghalaya. *Corresponding author email: pks_ageg@iari.res.in efforts in cole crops harvesting have been made, but existing machines are not efficient in selective harvesting. These harvesters used rotating cutter discs and operated at 0.6–1.5 km/h (Kanamitsu and Yamamoto 1996, El Didamony and El Shal 2020, Sarkar and Raheman 2021, Dixit and Rawat 2022). The selective mechanical harvesting and other agricultural operations have been explored in crops like broccoli, and cabbage incorporating image processing techniques for maturity detection. Robotic platforms with cameras and robotic arms have been developed for selective harvesting in cauliflower (Ramirez 2006, Blok *et al.* 2016, Singh *et al.* 2021). Parameters such as maturity detection, cutting speed, cutting position, shaft angular speed, and forward speed play crucial roles in developing a selective harvester for cauliflower.

Therefore, present study has been focused on development of a novel selective harvesting mechanism for cauliflower and the optimization of operating parameters in laboratory conditions using response surface methodology (RSM), which has been successfully applied in various fields (Jabbar *et al.* 2015, Mehmood *et al.* 2018, Malenga *et al.* 2022). The harvester is designed for small-scale growers in India, with minimal power requirements. The study

specifically investigates the Pusa Meghna and Pusa Sharad Indian cauliflower varieties, which lack prior research on selective harvesting. The findings hold significant potential for the development of an intelligent cauliflower harvester.

MATERIALS AND METHODS

The present study was carried out at ICAR-Indian Agricultural Research Institute, New Delhi during 2022–23, which consisted of a prototype harvesting unit, prototype pulling unit, and plant holding unit. During the design of laboratory setup, the physical properties of two cauliflower varieties, Pusa Meghna and Pusa Sharad, were assessed. Different physical properties, i.e. plant height (H_n), plant width (W_p), curd diameter (D_c), curd depth (DP_c), stalk diameter (D_s), and stalk length (L_s) were measured using 30 samples of each variety. The average measured values for H_p , W_p , D_c , DP_c , D_s , and L_s in Pusa Meghna were 54.6 \pm 3.17, 46 \pm 3.46, 11.3 \pm 2.31, 8.6 \pm 1.39, 3.11 \pm 0.22, and 9.13 ± 2.04 , respectively, while in Pusa Sharad these values were 61.5 ± 2.98 , 53.5 ± 2.19 , 15.6 ± 2.17 , $10.2 \pm$ 0.74, 3.7 ± 0.18 , and 5.4 ± 0.7 . The average stalk moisture content (wet basis) in both varieties at the maturity stage was ~75.51%. These measurements were further used for the design and development of the laboratory setup.

Experimental setup

A prototype of the cauliflower harvester was developed at Division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute, New Delhi during 2022–23. The harvester prototype encompassed three key components: the harvesting unit, prototype pulling unit, and plant holding unit (Fig 1A). These components were meticulously designed and integrated to create a functional and efficient system for harvesting cauliflowers.

Harvesting unit: The harvesting unit of the prototype consisted of a cauliflower maturity detection unit, actuating arm unit, and a cutting unit (Fig 1B). It was designed to be pulled by the prototype pulling unit using a wire rope, moving along a rail on the soil bin. The chassis of the harvesting unit was made of a hollow square MS pipe

 $(35 \times 35 \times 1.5 \text{ mm})$ with wheels (100 mm diameter) for mobility. The plants were securely held in the plant-holding unit. The cutting unit, located at the bottom of the actuating arm, operated when the maturity detection unit detected a mature curd. The actuating arm rotated, positioning the cutting unit perpendicular to the direction of travel for the cutting process. After cutting, the actuating arm returned to its original position. This cycle was repeated whenever a mature cauliflower curd was encountered during harvesting.

Maturity detection unit: The maturity detection unit consisted of an RGB camera, two arrays of LEDs for precise illumination control, and a microprocessor (Raspberry Pi 4B). An image of the cauliflower curd was captured using the RGB camera, and followed by image processing by the microprocessor using the OpenCV library to determine the curd diameter. The programming was implemented in Python. The operator also set a preset curd diameter. If the measured curd diameter was equal to or greater than the preset diameter, the curd was identified as mature, triggering the cutting process (Fig 1B).

Actuating arm unit: The actuating arm unit included a 20 mm solid shaft, a cutting unit carrier, and a servo motor. The shaft was connected to the cutting unit carrier on one end and linked to the servo motor through a flexible coupling on the other end. A servo motor (60 kg-cm) powered by a 7.4V Li-ion battery rotated the shaft. The angular speed of the servo motor was controlled by an Arduino UNO microcontroller. The cutting unit was enclosed within the cutting unit carrier $(200 \times 160 \times 150 \text{ mm})$ of 1 mm MS sheet.

Cutting unit: The cutting unit comprised of a chain-saw cutter, a brushless direct current (BLDC) motor, and a pulse width modulation (PWM) brushless motor controller driver. The cutting mechanism employed a 12-inch chain saw chain (pitch 0.375"), driven by a 300 W BLDC motor operating at a speed of 5200 rpm. The BLDC motor was powered by an 18V Li-ion battery (Fig 1B).

Prototype pulling unit: The prototype pulling unit included a rope and pulley transmission system, a guiding rail (C-section $50 \text{ mm} \times 25 \text{ mm} \times 5 \text{mm}$), a 3-phase induction motor, and a variable-frequency AC drive (VFD). The

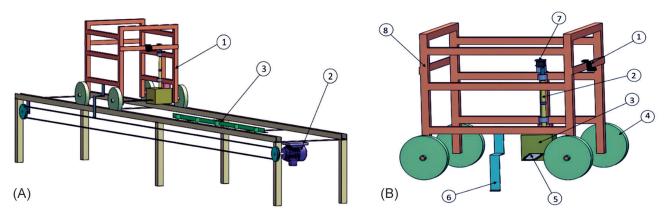


Fig 1 (A) Computer-aided design (CAD) model of laboratory setup: 1, Harvesting unit; 2, Prototype pulling unit; 3, Plant holding unit. (B) CAD model of harvesting unit: 1, Camera; 2, Solid rod; 3, Cutting unit carrier; 4, Wheel; 5, Cutting unit; 6, Connecting clamp; 7, Servo motor; 8, Chassis.

harvesting unit was securely connected to the wire rope using a 6 mm MS flat connecting clamp. Two cast iron pulleys were used (diameter 140 mm), with one as an idler and the other connected to the motor shaft. A 3-phase induction AC motor (5.5 kW, 1450 rpm) powered the pulling unit, pulling the harvesting unit via the wire rope. The forward speed of the harvesting unit was controlled by a VFD drive. The guiding rail (6 m length, width 0.68 m), provided a stable track for the harvesting unit.

Plant holding unit: The plant holding unit was constructed using an MS angle bar $(25 \times 25 \times 3 \text{ mm})$ with a hollow pipe (30 mm diameter, 65 mm length) welded at regular intervals of 45 cm on one side. Additional support was provided by welding a 40 cm length of MS flat (25 \times 2 mm) at the bottom. The plants were uprooted and their stalks were inserted into the hollow pipe sections of the plant holding unit. Nuts and bolts were used to securely fasten the stalks, ensuring stability during harvesting (Fig 1A).

Experimental plan: The evaluation of the harvesting system's performance was conducted on the Pusa Meghna and Pusa Sharad varieties at the Farm Power and Soil Dynamics Laboratory in ICAR-Indian Agricultural Research Institute, New Delhi. The experimental setup involved selecting three forward speeds for the harvesting unit, namely 0.5, 0.6, and 0.7 km/h. Additionally, three shaft angular speeds were chosen: 0.3, 0.35, and 0.4 rad/s. Three key responses were recorded to assess the system's performance: harvest success, damage rate, and cycle time. Harvest success was calculated as a percentage by dividing the number of successfully cut matured curds by the total number of real matured curds. The damage rate was measured as a percentage by dividing the sum of the total number of unripe harvested curds and the number of damaged curds after harvesting by the total number of harvested curds (Birrell et al. 2020). Lastly, cycle time represented the time required to harvest a single curd.

Response surface methodology approach: The optimization for harvest success $(Y_1^{\ 1}, \%)$, damage rate $(Y_2^{\ 1}, \%)$ and cycle time $(Y_3^{\ 1}, s)$ for the Pusa Meghna variety, and similarly, $Y_1^{\ 2}$ (%), $Y_2^{\ 2}$ (%), and $Y_3^{\ 2}$ (s) for the Pusa Sharad variety, were conducted using Response Surface Methodology (RSM). Two independent variables, namely forward speed $(X_1, km/h)$ and shaft angular speed $(X_2, km/h)$ rad/s), were considered in the experiment (Table 1). For the experiment, a face-centered central composite design with three levels and a quadratic model was employed for both varieties. A total of 11 treatments were randomly performed, which included four axial points, four fractional factorial points, and three central points, following the central composite design (CCD) methodology (Table 2). The real levels of the independent variables were coded to facilitate the analysis according to Eq. (1).

$$x_{i} = \frac{X_{i} - X_{i}^{*}}{\Delta X_{i}} \tag{1}$$

Where, the dimensionless coded value x_i was related to the corresponding uncoded value X_i of the ith independent

Table 1 Experiment plan for laboratory test

Independent variable	Symbol	Levels of coded variable		
	-	-1	0	+1
Forward speed (km/h)	X ₁	0.5	0.6	0.7
Shaft angular speed (rad/s)	X_2	0.30	0.35	0.40

variable. Furthermore, at the center point, the uncoded value of the i^{th} independent variable was denoted by X_i^* , while the step change value was defined as ΔX_i . The specific equations for X_1 and X_2 are presented below in Eqs. (2)–(3).

$$\mathbf{x}_1 = \frac{X_1 - 0.6}{0.1} \tag{2}$$

$$x_2 = \frac{X_2 - 0.35}{0.05} \tag{3}$$

The relationship between the predicted responses (harvest success, damage rate, and cycle time) and the independent variables was expressed using a second-degree polynomial equation. The equation, denoted as Eq. (4), is as follows:

$$Y = \beta_0 + \sum_{i=1}^{n} X_i \beta_i + \sum_{i=1}^{n} X_{ii} \beta_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} (4)$$

$$\beta_{i:} X_i : X_i + \epsilon$$

Where Y, is the predicted response; β_0 , the constant coefficient; β_i the linear coefficients; β_{ii} , the quadratic coefficients; β_{ii} the interaction coefficients; n, the number of factors studied in the experiments; and ε , the random error. Accordingly, X_i, and X_i, indicate the levels of the independent parameters.

Statistical analysis: The experimental data obtained were subjected to statistical analysis using Design Expert Software (version 8.0.6). The significance of the differences was determined using analysis of variance (ANOVA), with F-values calculated at significance levels of 0.05, 0.01, and 0.001. Three-dimensional response surface methodology (RSM) analyses were employed to identify the optimal operating conditions for the independent variables.

RESULTS AND DISCUSSION

Fitting the model: The effects of independent variables on harvest success, damage rate, and cycle time were determined using response surface methodology (RSM). RSM is a statistical, theoretical, and mathematical approach utilized for constructing models and optimizing the levels of independent variables. RSM derived regression equations, expressed in terms of uncoded factors enable the prediction of the response variable values and are presented in equations (5)–(10).

$$Y_{1}^{1} = -208.79 + 401.97X_{1} + 875.03X_{2} - 69.5X_{1}X_{2} - 305.60X_{1}^{2} - 1030.42X_{2}^{2}$$
 (5)

$$Y_{2}^{1} = 280.27 - 119.99X_{1} - 1490.98X_{2} - 136.0X_{1}$$
 (6)

$$X_{2} + 182.45X_{1}^{2} + 2339.79X_{2}^{2}$$
 (6)

$$Y_{3}^{1} = 21.59 - 24.17X_{1} - 42.13X_{2} + 15.5X_{1}X_{2} + 9.37X_{1}^{2} + 37.47X_{2}^{2}$$
 (7)

$$Y_2^{1} = 280.27 - 119.99X_1 - 1490.98X_2 - 136.0X_1$$

$$X_2 + 182.45X_1^{2} + 2339.79X_2^{2}$$
 (6)

$$Y_3^1 = 21.59 - 24.17X_1 - 42.13X_2 + 15.5X_1X_2 + 9.37X_1^2 + 37.47X_2^2$$
 (7)

Table 2 Experimental design with independent variables and experimental responses

Run no.	Independent variable		Response variables					
	Forward speed (km/h)	Shaft angular speed (rad/s)	Harvest success (%)		Damage rate (%)		Cycle time (s)	
			Y_1^{-1}	Y_1^2	Y_2^1	Y_2^2	$\overline{Y_3^1}$	Y ₃ ²
1	0.5	0.3	75.00	72.1	8.00	10.5	4.90	5.4
2	0.6	0.35	87.50	84.20	10.71	13.41	3.60	4.2
3	0.6	0.3	80.00	76.8	12.50	14.81	4.00	4.4
4	0.6	0.35	88.89	85.6	10.00	12.5	3.49	4.01
5	0.5	0.35	83.33	80.73	10.00	12.32	4.40	5
6	0.7	0.3	77.78	74.68	21.43	23.63	3.24	3.73
7	0.7	0.35	85.71	82.9	16.67	19	2.91	3.40
8	0.5	0.4	87.50	84.1	14.29	16.44	4.10	4.5
9	0.6	0.35	87.50	84.89	7.14	9.84	3.59	4.1
10	0.7	0.4	88.89	86.01	25.00	27.39	2.75	3.29
11	0.6	0.4	90.00	87.5	22.22	24.92	3.31	3.9

$$Y_1^2 = -207.16 + 382.89X_1 + 879.88X_2 - 33.5X_1X_2 - 300.05X_1^2 - 1066.21X_2^2$$
 (8)

$$Y_2^2 = 276.0 - 99.68X_1 - 1487.19X_2 - 109.0X_1 X_2 + 157.58X_1^2 + 2312.31X_2^2$$
(9)

$$Y_3^2 = 20.58 - 26.06X_1 - 30.54X_2 + 23.0X_1X_2 + 8.79X_1^2 + 15.16X_2^2$$
 (10)

The statistical analysis (ANOVA) confirmed that the experimental data could be effectively represented by a second-order polynomial model. The models were significant for both varieties. The coefficient of determination (R²) values obtained for harvest success (Meghna: 0.9784, Sharad: 0.9898), damage rate (0.8903, 0.8943), and cycle time (0.9960, 0.9819) indicated a strong fit of the model to the data. The lack of fit was found to be non-significant, further validating the accuracy of the model. The high R² values demonstrated that the quadratic polynomial model

adequately describes the influence of forward speed and shaft angular speed on the response variables.

Effect of independent variables on response variables

Harvest success: In both varieties, the harvest success was significantly influenced by the forward speed of the harvesting unit (Table 3). Lower forward speeds resulted in low harvest success due to inadequate pushing force, leading to poor curd detachment. Harvest success was approximately 83% for Meghna and 80% for Sharad (Fig 2A and 2D). Slightly higher harvest success was observed for Meghna, possibly due to easier detachment and better camera visibility. At medium forward speeds, harvest success improved to 88% for Meghna and 84% for Sharad. However, further increase in forward speed led to decline in harvest success. Higher speeds posed challenges in effectively cutting all mature cauliflower heads (Kanamitsu and Yamamoto 1996). The maximum forward speed was

Table 3 Mean sum of square of responses obtained from different operating parameters in two varieties of cauliflower

Source	df	Harvest success		Damage rate		Cycle time	
		Pusa Meghna	Pusa Sharad	Pusa Meghna	Pusa Sharad	Pusa Meghna	Pusa Sharad
Model	5	50.19***	51.22***	68.37*	67.09*	0.823***	0.798***
X_1	1	7.15*	7.39**	158.21**	157.70**	3.375***	3.345***
X_2	1	188.7***	193.01***	63.90*	65.41*	0.653***	0.564***
X_1X_2	1	$0.48^{ m NS}$	$0.11^{\rm NS}$	1.85^{NS}	1.19^{NS}	0.024*	0.053*
X_1^2	1	23.66**	22.81***	$8.43^{ m NS}$	$6.29^{ m NS}$	0.022^{NS}	0.020^{NS}
X_2^2	1	16.81**	18.00***	86.68*	84.66*	0.022^{NS}	$0.004^{ m NS}$
Residual	5	0.55	0.26	7.16	7.28	0.002	0.007
Lack of fit	3	$0.49^{ m NS}$	$0.11^{\rm NS}$	9.56^{NS}	$9.84^{ m NS}$	$0.000^{ m NS}$	0.006^{NS}
Pure error	2	0.64	0.49	3.57	3.44	0.004	0.009
Core total	10						

^{*, **, ***} significant at P=0.05, 0.01 and 0.001, respectively, NS Non-significant.

limited to 0.7 km/h (Tewari *et al.* 2020). The shaft angular speed had a significant impact on harvest success, increasing it by 13% for Meghna and 17% for Sharad. Lower speeds caused insufficient push force and plant bending (Fig

2A and 2D). The interaction effect of the model was not significant (Table 3).

Damage rate: Forward speed had a significant linear effect on the damage rate for both varieties, with an upward

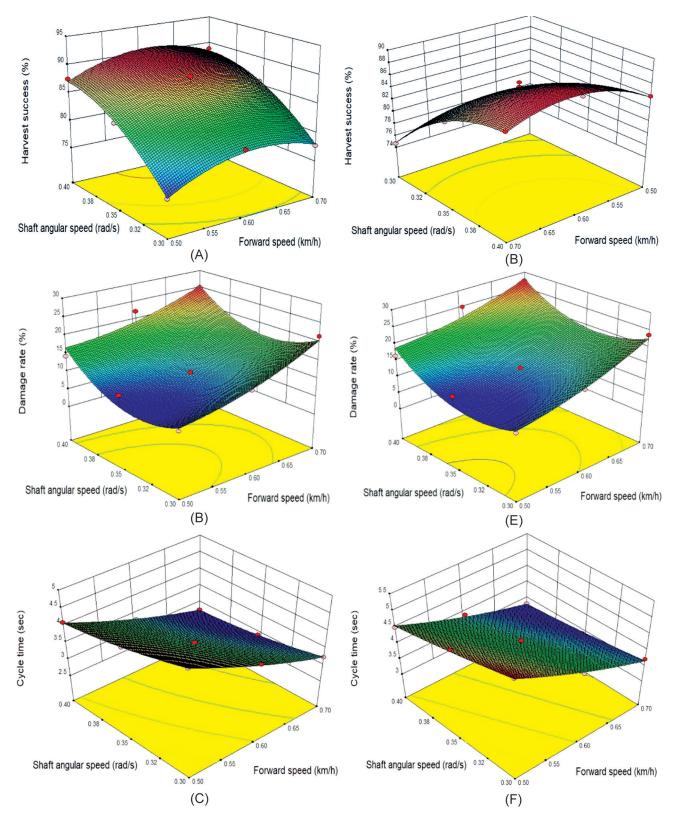


Fig 2 Combined effect of forward speed and shaft angular speed on: (A), harvest success of Pusa Meghna; (B), damage rate of Meghna; (C), cycle time for Meghna; (D), harvest success of Pusa Sharad; (E), damage rate of Sharad and; (F), cycle time for Sharad.

trend while increasing forward speed (Table 3). Increasing the forward speed from 0.5-0.7 km/h nearly doubled the damage rate in both varieties (Fig 2B and 2E). Blade slippage relative to the stem may have caused increased curd damage at higher speeds (Dixit and Rawat 2022). The linear term of shaft angular speed also significantly contributed to the damage rate for both varieties, with a positive correlation (Table 3). Increasing shaft angular speed from 0.3–0.4 rad/s resulted in ~7% increase in the damage rate (Fig 2B and 2E). The Sharad variety exhibited slightly higher damage rates due to poor curd classification caused by limited visibility. The interaction effect of the model was non-significant (Table 3). The medium level of shaft angular speed showed slightly lower damage compared to the low level, as slower cutting speed at the low level caused the curd to stick to the blade and result in damage.

Cycle time: In both varieties, forward speed, shaft angular speed and their interaction effect had shown significant effect on the cycle time (Table 3). The contour plot visually illustrates the cycle time as a function of forward and shaft angular speed (Fig 2C and 2F). Both parameters had negative correlation with the cycle time. Increasing the forward speed from 0.5–0.7 km/h led to a 30% reduction in cycle time, due to increased pushing force leading to rapid cutting. However, increasing the shaft angular speed from 0.3–0.4 rad/s decreased the cycle time by ~13%, attributing to reduced stalk resistance during cutting (Sarkar and Raheman 2021).

Optimization of independent variables: Response surface graphs illustrate the effects of the operating parameters on the response variables for the both varieties. These graphs visually depict the interactions among the independent variables. Numerical optimization was then performed using the desirability function to determine the optimal operating parameters for higher harvest success, lower damage rate, and minimum cycle time. The optimized settings were found to be 0.62 km/h for forward speed and 0.36 rad/s for shaft angular speed for both varieties. The predicted values for harvest success, damage rate, and cycle time at the given settings were as follows: for Pusa Meghna, 89.12% harvest success, 12.31% damage rate, and 3.35 seconds cycle time (Fig 2A, 2B, and 2C), and for Pusa Sharad, 86.19% harvest success, 14.95% damage rate, and 3.89 seconds cycle time (Fig 2D, 2E, and 2F).

Verification of RSM model: The model's suitability for predicting response values was assessed by validating the optimized operating parameters. Experiments were conducted using the optimized settings, and the obtained response values were compared with the predicted values. The experimental response values for the Pusa Meghna variety were 91.94% harvest success, 12.08% damage rate, and 3.12 seconds cycle time, while for the Pusa Sharad variety, the values were 83.95% harvest success, 14.73% damage rate, and 4.05 seconds cycle time. The experimental response values closely matched the predicted values and the prediction errors for the Pusa Meghna variety were 3.07% for harvest success, 1.9% for damage rate, and

4.73% for cycle time. For the Pusa Sharad variety, the prediction errors were 2.67% for harvest success, 1.5% for damage rate, and 3.92% for cycle time. Weicai *et al.* (2016) described the method for calculation of prediction error (Eq. 11) and the prediction errors, which below $\pm 10\%$, provide further assurance of the accuracy and validity of the developed models.

$$\frac{\text{Prediction}}{\text{error (\%)}} = \frac{\text{Experimental value-Predicted value}}{\text{Experimental value}} \times 100 (11)$$

This study evaluated a laboratory-scale single row selective harvesting system and successfully designed a prototype based on plant physical properties. Experimental trials on Pusa Meghna and Pusa Sharad cauliflower varieties revealed the significant influence of forward speed and shaft angular speed on harvest success, damage rate, and cycle time. Higher damage rates were observed at increased speeds, while lower cycle times were achieved at higher values of these parameters. The optimized operating parameters were determined as 0.62 km/h forward speed and 0.36 rad/s shaft angular speed, with a desirability of 0.80 for both varieties. At these optimized settings, the performance of the developed harvester was enhanced. The determined optimal values will be implemented in a field prototype selective cauliflower harvester for successful operation in agricultural farms.

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